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## NEW RESULTS ON PRECISION STUDIES OF HEAVY VECTOR BOSON PHYSICS

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We present new results for two important heavy vector boson physics processes: (1), virtual corrections to hard bremsstrahlung which are relevant to precision predictions for the radiative return process in Z boson production at and beyond LEP2 energies ; and, (2), electric charge screening effects in single W production with finite  $p_T$ , multiple photon radiation in high energy collider physics processes. In both cases we show that we improve the respective precision tag significantly. Phenomenological implications are discussed.

*Keywords:* Bremsstrahlung; W/Z Bosons; Screening.

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## 1. Introduction

Electroweak(EW) [1] and QCD [2] loop corrections are established: precision LEP [3] physics,  $m_t$  [4], ..., set a stage for 1 GeV - 1 TeV high precision Standard Model [1,2] tests via theoretical predictions for both signal and background processes in high energy colliding beam environments. In the EW sector, this now requires exact  $\mathcal{O}(\alpha^2)$ ,  $\mathcal{O}(\alpha^3 L^3)$ , where  $L$  is the respective big log, on an event-by-event basis in such studies as radiative return from 1-2 GeV to the  $\pi\pi$  resonance regime in Daphne and the asymmetric B-Factories, radiative return from 200 GeV to the Z pole in final LEP2 data analysis, Z factory physics at ILC, ... .

In this paper, we present new results on two aspects of such precision studies: (1), the virtual correction to  $1\gamma$ -bremsstrahlung; (2), electric charge screening in  $1W$  production [5] – see also Ref. [6] in this connection.

## 2. Virtual Corrections to Hard Bremsstrahlung

For the process  $e^+e^- \rightarrow \bar{f}f + \gamma$ , we compare in Fig. 1 the calculations in Refs. [7–10] at the  $\bar{\beta}_1^{(2)}$  level for initial state radiation, where  $\{\bar{\beta}_n\}$  are the standard YFS [11] residuals. The result by Ref. [7], labeled IN in the figure, is exact and fully differential but without complete mass corrections, the result in Ref. [8], labeled BVNB, is exact with the complete mass corrections but is integrated over the photon azimuthal angle, the result of Ref. [9], labeled JMWY, is fully differential with the complete mass corrections following the method of Ref. [12] whereas the exact result of Ref. [10], labeled KR, is also fully differential with complete mass corrections included in an entirely different way from that used in Ref. [9]. The agreement shown in the figure is at the  $3 \times 10^{-5}$  level in units of the Born  $e^+e^- \rightarrow \bar{f}f$  cross section for an energy cut at  $v_{max} = 0.9625$ .

## 3. Electric Charge Screening Effects in $1W$ Production

Electric charge screening(ECS)/Leading Log scale transmutation(LLST) [5, 6] is known from low angle Bhabha scattering [13] –  $L(s) \equiv \ln \frac{s}{m_e^2} \Rightarrow L(|t|)$  in the LL expansion. In Ref. [5], we have found in the toy model

$$\mu^-(p_a) + \mu^+(p_b) \rightarrow \mu^-(p_c) + \mu^+(p_d) + \gamma(k) \quad (1)$$

the ECS corrected weight

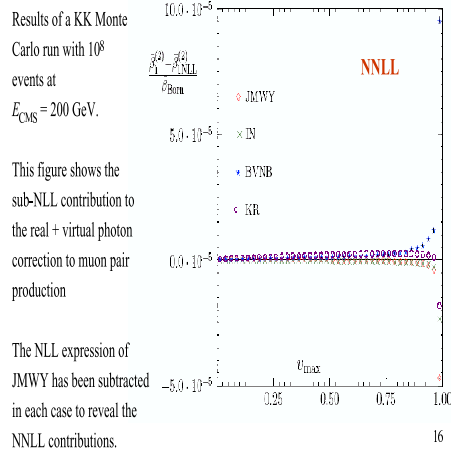
$$\tilde{S}_{ab}(k)W_{\text{ECS}}(k) \quad (2)$$

for the ISR IR emission factor  $\tilde{S}_{ab}(k)$  [11, 13] where

$$W_{\text{ECS}}(k) = \frac{\tilde{S}_{abcd}(k)}{\tilde{S}_{ab}(k) + \tilde{S}_{cd}(k)}, \quad (3)$$

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## Monte Carlo Results

Fig. 1. Sub-NLL contribution  $\beta_1^{(2)} - \beta_{1\text{NLL}}^{(2)}$ .

in a standard YFS notation. For the single W production  $e^-e^+ \rightarrow f_c(p_c) + \bar{f}_d(p_d) + f_e(p_e) + \bar{f}_f(p_f)$  we find that we can do the same:

$$W_{\text{ECS}}^{\text{real}} = \prod_i w^R(k_i), \quad w^R(k) = \frac{\tilde{S}_{ab}(k) + \tilde{S}_{CD}(k) + \tilde{S}_{aC}(k) + \tilde{S}_{bD}(k) + \tilde{S}_{aD}(k) + \tilde{S}_{bC}(k)}{\tilde{S}_{ab}(k) + \tilde{S}_{CD}(k)}. \quad (4)$$

for the effective [5] final particles 'C' and 'D' close to the incoming beams, as we illustrate in Fig. 2. A factor  $\exp(\Delta U)$  cancels *exactly* the dummy [5] IR  $\epsilon$ -dependence and compensates *approximately* for the normalization change due to the  $\langle W_{\text{ECS}}^{\text{real}} \rangle$  weight and the effective coupling is also that at  $|t|$ , by standard renormalization group [14] arguments; this all is realized [5] with the normalization correction (here,  $\gamma_r \equiv \frac{2\alpha}{\pi}(L(|r|) - 1)$ ,  $\gamma_t \equiv \frac{1}{2}(\gamma_t + \gamma_s)$ )

$$W_{\text{ECS}}^{\text{norm}} = \exp\left(\frac{3}{4}(\tilde{\gamma}_t - \gamma_s)\right) \exp(\Delta U(\epsilon))$$

$$\Delta U(\epsilon) = U(\epsilon) - U_R(\epsilon), \quad U(\epsilon) = \int_{\epsilon\sqrt{s}/2}^{\sqrt{s}} \frac{d^3k}{k^0} \tilde{S}_{ab}(k), \quad U_R(\epsilon) = \int_{\epsilon\sqrt{s}/2}^{\sqrt{s}} \frac{d^3k}{k^0} \tilde{S}_{ab}(k) w^R(k). \quad (5)$$

to maintain the exact IR cancellation in the MC (KoralW [5, 15], for example).

The only purpose of the weight  $W_{\text{ECS}}^{\text{real}}$  is to restore the ECS effect due to  $\text{ISR} \otimes \text{FSR}$  interference. We do not aim at re-creating the FSR. This would be formally possible with a similar weight; however, the resultant weight distribution would be bad and the attendant MC calculation would not be convergent. We get  $W_{\text{ECS}}^{\text{real}} \rightarrow 1$  for photons collinear with the FS effective fermions  $C$  and  $D$ . This ensures a very good weight distribution. The FSR can be treated separately, either inclusively (calorimetric acceptance) or exclusively, generated with the help of

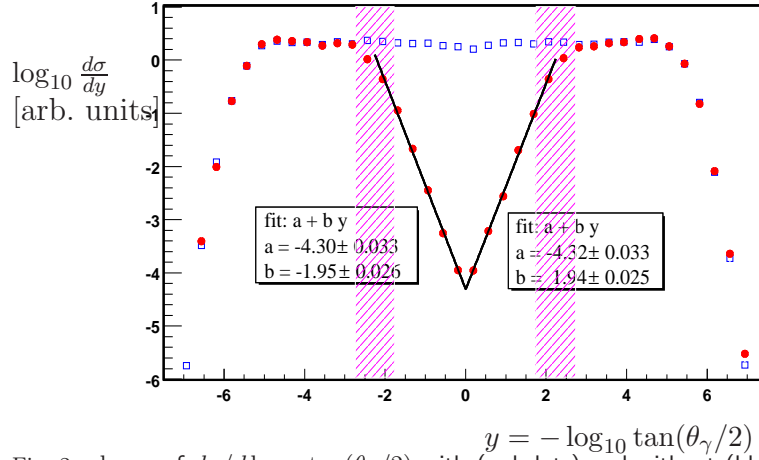


Fig. 2.  $\log_{10}$  of  $d\sigma/d\log_{10}\tan(\theta_\gamma/2)$  with (red dots) and without (blue open squares) the ECS correction, arbitrary units. In boxes the values of fits are shown.

PHOTOS [16]<sup>a</sup>. The precision tag of  $\leq 2\%$  is realized [5] – good enough for final LEP2 data analysis.

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<sup>a</sup>Care has to be taken to implement ECS for FSR, if necessary.

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